Associated photon and heavy quark production at high energy within k_T-factorization

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Abstract. In the framework of the k_T-factorization approach, the production of prompt photons in association with a heavy (charm or beauty) quarks at high energies is studied. The consideration is based on the $O(\alpha\alpha_s^2)$ off-shell amplitudes of gluon-gluon fusion and quark-(anti)quark interaction subprocesses. The unintegrated parton densities in a proton are determined using the Kimber-Martin-Ryskin prescription. Our numerical predictions are compared with the D0 and CDF experimental data. Also we extend our results to LHC energies.

INTRODUCTION

Recently the D0 and CDF Collaborations reported data [1, 2, 3] on associated (with a heavy quark jets) prompt photon production at the Tevatron. The D0 Collaboration showed that the measured cross sections are in agreement with the NLO QCD predictions [4] within theoretical and experimental uncertainties in the region up to $p_T^\gamma \sim 70$ GeV. However, the substantial disagreement between theory and data for both $\gamma + b$-jet and $\gamma + c$-jet production at large p_T^γ was observed. The cross section slopes in data significantly differ from the predicted ones. The results indicate a need for higher order perturbative QCD corrections in the large p_T^γ region.

In the D0 papers [1, 3] it was demonstrated also that the k_T-factorization predictions [5] are in a better agreement with the data.

First application of k_T-factorization approach to production of photons associated with the charm or beauty quarks have been performed in our previous paper [6]. The consideration was based on the $\mathcal{O}(\alpha\alpha_s^2)$ amplitude for the production of a single photon associated with a quark pair in the fusion of two off-shell gluons $g^*g^* \to \gamma Q\bar{Q}$. A good agreement between the numerical predictions and the Tevatron data was obtained in the region of relatively low p_T^γ where off-shell gluon fusion dominates. However, the quark-induced subprocesses become more important at moderate and large p_T^γ and therefore should be taken into account. Here we extend a previous predictions [6] by including into the consideration two additional $\mathcal{O}(\alpha\alpha_s^2)$ subprocesses, namely $q\bar{q} \to \gamma Q\bar{Q}$ and $q(\bar{q})Q \to \gamma q(\bar{q})Q$, where Q is the charm or beauty quark [5].

THEORETICAL FRAMEWORK

According to the k_T-factorization theorem, the cross section of the prompt photon and associated heavy quark production can be written as a convolution of the relevant off-shell partonic cross sections and unintegrated parton distribution functions (uPDF) in the proton $f_{i,j}(x, \mathbf{k}_T^2, \mu^2)$:

$$\sigma = \sum_{i,j} \int \hat{\sigma}_{ij}(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2)\, f_i(x_1, \mathbf{k}_{1T}^2, \mu^2) f_j(x_2, \mathbf{k}_{2T}^2, \mu^2)\, dx_1 dx_2\, d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi},$$

where $\hat{\sigma}_{ij}(x_1, x_2, \mathbf{k}_{1T}^2, \mathbf{k}_{2T}^2), (i, j = q, g)$ is the relevant partonic cross section. The initial off-shell partons have fractions x_1 and x_2 of initial protons longitudinal momenta, non-zero transverse momenta $\mathbf{k}_{1T}$ and $\mathbf{k}_{2T}$ and azimuthal angles ϕ_1 and ϕ_2.

In what concerns the uPDF, we took them in the KMR form [7]. The KMR formalism is a prescription for constructing the uPDF from the known standard PDF [1]. It gives k_T-dependent uPDF for both gluon and quark.

The analytic expressions of the corresponding off-shell matrix elements were listed in [5]. In the k_T-factorization approach the gluon polarization density matrix takes so called BFKL form: $\sum \varepsilon^\mu \varepsilon^{*\nu} = k_T^\mu k_T^\nu / \mathbf{k}_T^2$. The spin density matrix for the off-shell spinors is taken in the form $u(q)\bar{u}(q) = x\hat{p}$, where q and p are the quark and the proton momenta in the small x and massless approximation [5].

In our numerical calculations we took the renormalization and factorization scales $\mu_R^2 = \mu_F^2 = \xi^2 p_T^2$. In order to evaluate theoretical uncertainties, we varied ξ between $1/2$ and 2 about the default value $\xi = 1$. We used the LO formula for the strong
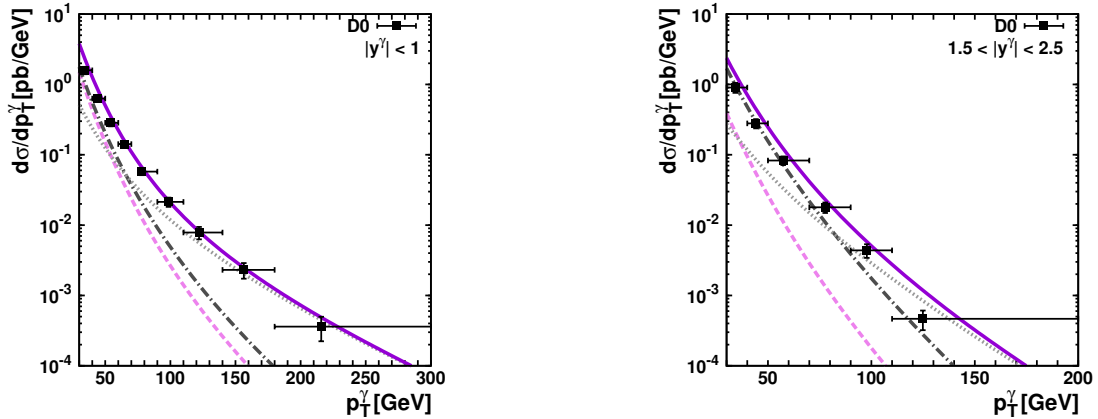

FIGURE 1. Differential cross section $d\sigma/dp_T^\gamma$ of associated $\gamma + b - jet$ production at $\sqrt{s} = 1960$ GeV, $|y^{jet}| < 1.5$ and $p_T^{jet} > 15$ GeV. The dashed, dotted and dash-dotted curves correspond to the contributions of $gg \to \gamma Q\bar{Q}, q\bar{q} \to \gamma Q\bar{Q}, q(\bar{q})Q \to \gamma q(\bar{q})Q$ subprocesses. The solid curve represents their sum. The experimental data are from [1].

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[1] Numerically, we used the MSTW-2008 set [8] in the proton as the input.

coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavours at $\Lambda_{QCD} = 200$ MeV, so that $\alpha_S(M_Z) = 0.1232$. We set the charm and beauty quark masses to $m_c = 1.5$ GeV and $m_b = 4.75$ GeV. We use the experimental isolation cut for produced photons [1, 2, 3]:

$$E_T^{had} \leq E^{max}$$

$$(\eta^{had} - \eta)^2 + (\varphi^{had} - \varphi)^2 \leq R^2.$$

We took $R = 0.4$ and $E^{max} = 1$ GeV as in the Tevatron experimental data. The isolation not only reduces the background from the secondary photons produced by the decays of π^0 and η mesons but also significantly reduces the so called fragmentation components, connected with collinear photon radiation (10%).

Similarly to the traditional QCD approach the calculated cross section split into two pieces:

$$d\sigma = d\sigma_{direct}(\hat{\mu}^2) + d\sigma_{fragm}(\hat{\mu}^2),$$

where $d\sigma_{direct}(\hat{\mu}^2)$ is the perturbative contribution, $d\sigma_{fragm}(\hat{\mu}^2)$ is the fragmentation contribution, and $\hat{\mu}^2$ is the fragmentation scale. In our calculations $\hat{\mu}$ is the invariant mass of the produced photon and any final quark and we restrict the direct contribution to $\hat{\mu} > M = 1$ GeV in order to eliminate the collinear divergences in the direct cross section. Then the mass of light quark can be safely sent to zero.

NUMERICAL RESULTS

In Figs. 1 – 3 some of the results of our calculation [5] are shown (more details see in [5]). We have found that the full set of experimental data is reasonably well described by the k_T-factorization approach. One can see that the property of the uintegrated parton distribution and the non-vanishing transverse momentum of the colliding partons lead
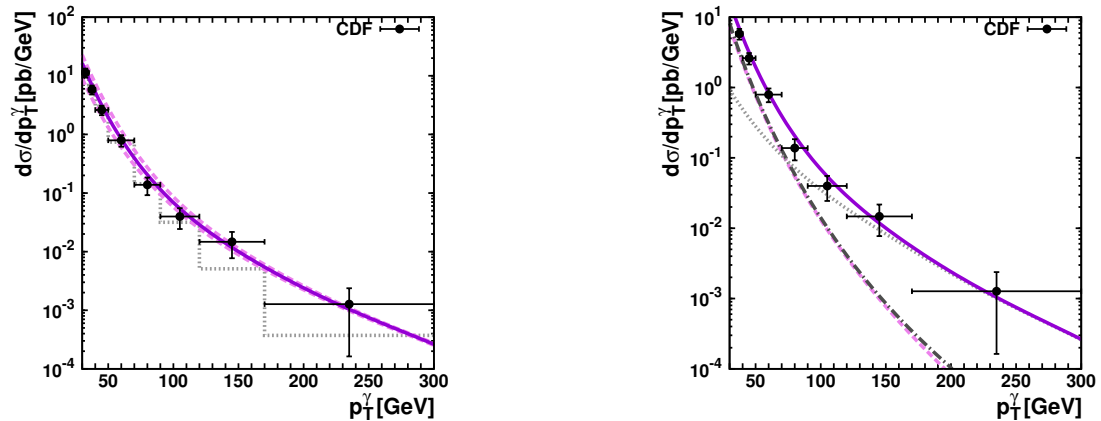

FIGURE 2. Differential cross section $d\sigma/dp_T^\gamma$ of associated $\gamma + c - jet$ production at $\sqrt{s} = 1960$ GeV, $y^\gamma < 1, |y^{jet}| < 1.5$ and $p_T^{jet} > 20$ GeV. Notaion of all curves on right panel is the same as in Fig. 1. The dotted histogram is the NLO pQCD predictions [4] taken from [2]. The experimental data are from [2].
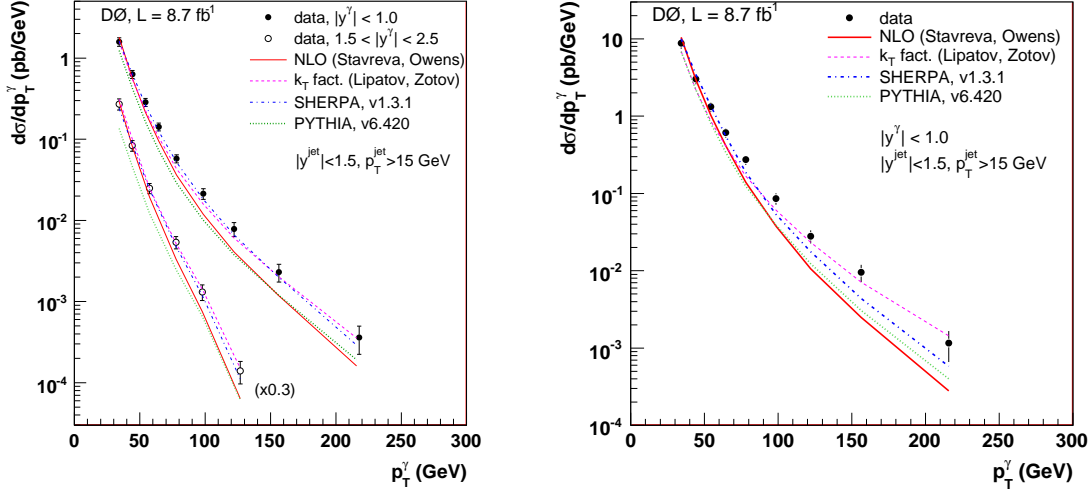
FIGURE 3. Differential cross section $d\sigma/dp_T^\gamma$ of associated $\gamma + b - jet$ (left panel) and $\gamma + c - jet$ (right panel) production at $\sqrt{s} = 1960$ GeV. Figs. are taken from [1, 3].

to a broadering of the photon transverse momentum distributions in comparision with the collinear pQCD results. As it was noted in [1, 3] our results agree better with the Tevatron data than the NLO QCD ones (see Fig. 3)

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